Similarity of Turbulent Wall Fires

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This study was undertaken to help resolve the general flammability problem - namely, to predict heat release rates and fire spread rates in terms of readily measured material flammability properties. At present much of the problem is understood; however we do not have established procedures for predicting the radiative heat transfer to adjacent fuel surfaces. These predictions must be quite accurate because upward spread and burning processes are very sensitive to flame heat transfer from the flames due to positive feedback. The present work parallels Markstein's[1,2] investigation of the radiant heat transfer blockage by the cold gas and soot near the fuel surface. Here we are concerned with the soot and temperature profiles responsible for the radiant emission from the flames. The results show the profiles remain geometrically similar for a fixed overall fuel to entrained air equivalence ratio corresponding to a fuel mass transfer rate, $\dot{m}''$, which increases with the square root of height, Z.

Various pyrolysis zone heights were simulated by supplying propylene to up to ten 132mm high and 320 mm wide water-cooled sintered-metal gas burners. The forward heat transfer zone was simulated by a 660mm high water-cooled heat transfer plate mounted above the gas burners. The flow was maintained two-dimensional by 150mm deep water-cooled side walls attached to the burner apparatus over its entire height.

The thickness of the soot layer, δ_s, was measured by inserting arrays of 5mm glass rods into the flames perpendicular to the wall surface and rapidly withdrawing them after a two second exposure to the flames. The soot layer thickness was determined from the average length of soot deposit on ten rods.

Figure 1 shows the length ratio, Z/δ_s, correlated against the inverse modified equivalence ratio $\rho_A(2gZ)^{1/2}/(\dot{m}''-\dot{m}_o'')$. The modification of the equivalence ratio is required because the soot vanishes and the flames become blue for mass transfer rates less than $\dot{m}_o''=4$ g/m^{2}s. As a result of wall cooling and dilution by the products of combustion at low mass transfer rates, the data show that the cut-off, $\dot{m}_o''$, is independent of Z. The turbulent motion typically transports the luminous soot (e.g. visible flames) out into the incoming air all the way to where the mean gas temperature drops to around 1000 K. The correlation says that the soot layer thickness is proportional to Z for a given ratio of entrained air, $\rho_A(2gZ^3)^{1/2}$ to supplied fuel $\dot{m}''Z$ above its blue flame value $\dot{m}_o''Z$. The correlation extends over a very wide range of flame equivalence ratios.

Temperature profiles across the flame boundary layer were measured by a thermocouple rake consisting of 15 insulated Chromel-Alumel thermocouples inside 1.6 mm diameter Inconel sheaths spaced 12.6 mm on center and protruding 1 cm downward into the rising flow. The measured temperatures inside the flame were significantly depressed by radiation heat loss. On the other hand, the thermocouple temperatures outside the flame were significantly increased by radiant heat transfer from the flame. We corrected for both these effects with a simple heat transfer model to obtain the correlations shown in Figure 2. The vertical dashed line at $y/\delta=1$ shows the boundary of the soot layer occurring at temperatures near T=1000K. Inside the soot layer, the presence of cold fuel is seen by the temperature drop near the wall. Outside the soot layer, the mixing of combustion products with the entrained air causes the corrected temperatures to asymptotically approach the ambient temperature as y/δ increases. These outer temperature profiles correlate reasonably well when plotted against $(y-\delta)/Z$.

Markstein[2] reports measurements of the extinction of infrared radiation, ε_o, by soot (at wavelengths λ_o = 0.9 μm and 1.0 μm) across the flame boundary layer. These measurements immediately provide the integral of the soot volume fraction, $f_v\delta_s$, across the flame, $f_v\delta_s=-\lambda_o\, ln(1-\varepsilon_o)/7$, which is replotted here in Figure 3 using coordinates similar to those in Figure 1. The factor of 7 in the above expression is recommended by Hottel and Sarofim[3] for soot. The correlation is not as good as for the soot standoff distance (Figure 2), apparently because the soot volume fraction, f_v, depends weakly on the flow time.

The faired curves in Figure 3 indicate that the fractional conversion of fuel carbon to soot, χ_s, at a fixed mass transfer rate (1) initially increases proportional to the flow time up to a height Z=0.75 m for the C_3H_6 flames, and then (2) becomes constant at greater heights.

Figure 4 shows the measured transverse temperature profiles for four C_3H_6 flames at two heights and two equivalence ratios, $\dot{m}/Z^{1/2}$ near 11 and 26 g/m$^{5/2}$s respectively. Notice the dependence of profile-shape on equivalence ratio, but almost perfect similarity at fixed equivalence ratios. Theory suggests that the heat release by combustion per unit wall height increases with $Z^{1/2}$ at fixed equivalence ratio. The present data suggest that the soot and gas radiation initially increase almost linearly with height for small Z where radiation is unimportant, but convective heat loss is important. At somewhat greater heights the radiation increases more nearly with $Z^{1/2}$ due to radiant heat loss. Ultimately the radiation will level off at very large Z after the flames become optically thick.

The similarity of combustion observed in this study greatly eases the task of analyzing experimental data and will make it much easier to tailor future detailed semi-empirical turbulent combustion models, so that their predictions exactly agree with experiment (at least for situations having $\dot{m}'' \sim Z^{1/4}$). One rarely finds such true similarity (i.e. reducible to one-dimensional behavior) in combustion, especially turbulent buoyant combustion.

References

1. Markstein, G.H. and de Ris, J.: Twenty-Fourth Symposium (International) on Combustion, 1747, The Combustion Institute, 1992.
2. Markstein, G.H.: Personal Communication, 1994.
3. Hottel, H.C., and Sarofim, A.F. (1962), *Radiative transfer*, McGraw-Hill, New York, p. 199,

Correlation of Soot Stand-Off Distance
C_3H_6 Wall Fires

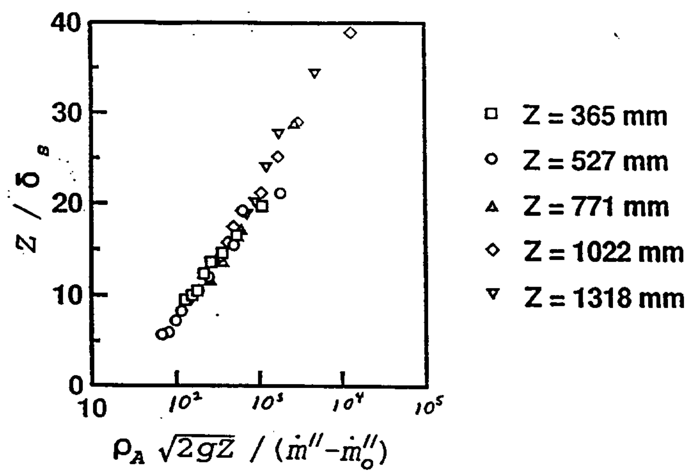


Figure 1.

Corrected Temperature Map
C_3H_6 8 Burners Z = 1.022 m

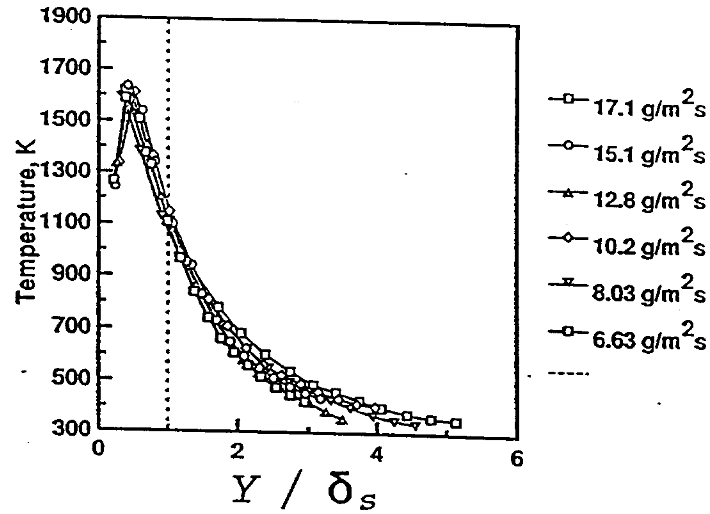
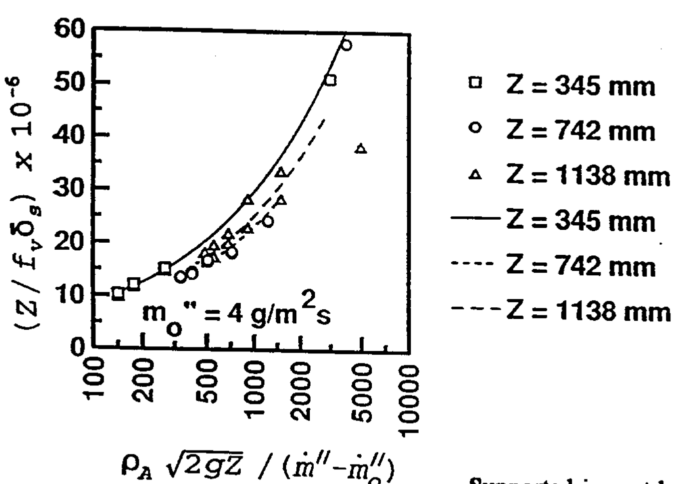
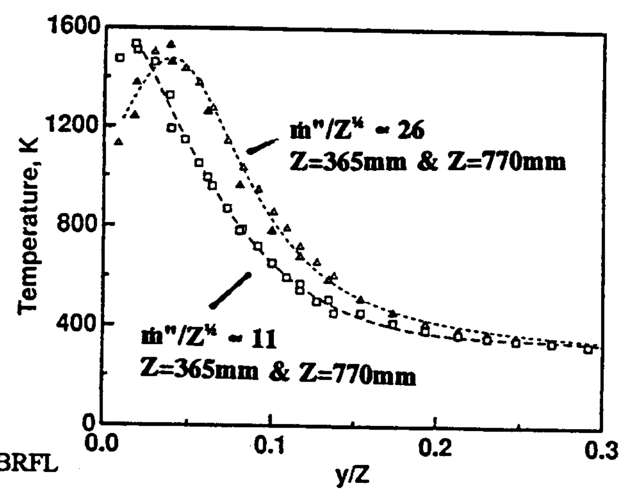


Figure 2.

C_3H_6 Wall Fires



Similarity of Temperature Profiles



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